Developing a precautionary ecosystem approach to managing fisheries and other marine activities at Heard Island and McDonald Islands in the Indian Sector of the Southern Ocean

by

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ABSTRACT. - Conservation of marine biodiversity and sustainable use of marine resources in the vicinity of Heard Island and McDonald Islands (HIMI) have been important goals for the Australian Government since 1980 when it signed the Convention on the Conservation of Antarctic Marine Living Resources. The evolving marine policy, legal and regulatory framework within Australia, combined with its international obligations, have provided a strong foundation for the precautionary, ecosystem based approach to achieving its goals for managing of marine resources and conserving biodiversity conservation in the region. The elements of the approach can be summarised as (i) the precautionary approach to setting catch limits for target species, (ii) a strategy for managing bycatch in the fisheries, notably mitigation of seabird mortality and minimising the bycatch of finfish species, (iii) spatial management of activities to conserve representative areas of marine biodiversity in the region and to avoid fishing causing significant harm to benthic habitats, (iv) mitigation of indirect effects of fisheries on food webs, and (v) elaboration of approaches to adjust fishing in the event of climate change or other impacts on the ecosystem. Here, we detail each of the elements of the approach aimed at achieving the objectives of conservation and sustainable use of marine biodiversity in the HIMI region, and illustrate the scientific principles and research being used to facilitate achieving these objectives. The experience at HIMI shows that the precautionary approach can advance the development of fisheries and achieve environmentally sustainable outcomes in cases when there are few data at the beginning. It shows that correction of early mistakes (assumed higher than actual productivity of the stock along with overharvesting by illegal operators) is possible without suffering substantial loss to the fishery. A key lesson is in the acquisition of data and the development of management measures in advance of the full development of the fishery and a process by which management measures can be readily agreed by stakeholders and adjusted as problems are identified. An important challenge remaining to be addressed is how to account for the change in status of the stocks and the ecosystem and the respective roles that fisheries and climate change have in causing those changes across the Kerguelen Plateau.

RÉSUMÉ. - Développement d'une approche écosystémique de précaution pour gérer les pêcheries et les autres activités marines aux îles Heard et MacDonald, secteur indien de l'océan Austral.

La conservation de la biodiversité marine et l'utilisation rationnelle des ressources marines autour des îles Heard et MacDonald (HIMI) ont été des objectifs majeurs pour le gouvernement australien depuis 1980 lorsqu'il a signé la Convention pour la Conservation des Ressources marines vivantes de l'Antarctique. Le cadre légal et réglementaire de la politique maritime en vigueur en Australie aussi bien que ses obligations internationales ont été à la base du fondement d'une approche précautionnelle de type écosystèmique afin de remplir ces objectifs de gestion et de conservation dans la région. Les éléments de l'approche peuvent être résumés comme suit: (i) une approche de précaution pour l'établissement des limites de captures des espèces visées par la pêche, (ii) une stratégie de gestion pour les captures accessoires, notamment la mise en place de mesures de réduction de la mortalité accidentelle des oiseaux marins et de moyens pour minimiser les captures accessoires de poissons non ciblés par la pêche, (iii) une gestion spatiale des activités pour préserver des aires représentatives de biodiversité marine dans la région et éviter que la pêche conduise à une altération significative des habitats, (iv) la réduction des effets indirects des pêches sur les réseaux trophiques et (v) l'élaboration d'approches pour ajuster la pêcherie en fonction d'éventuels changements climatiques ou de tout autre impact sur l'écosystème. Nous détaillons ici chacun des éléments de cette approche basée sur la réalisation des objectifs de conservation et d'utilisation rationnelle de la biodiversité marine dans la région HIMI et illustrons les principes scientifiques et la recherche développés pour atteindre ces objectifs. L'expérience acquise en zone HIMI montre que l'approche de précaution peut faire progresser le développement des pêches et générer des résultats environnementaux supportables dans les cas ou il y a peu de données au départ. Cela montre que la correction des erreurs initiales (en considérant une plus importante productivité du stock qu'à présent, due à la surexploitation d'opérateurs illégaux) est possible sans pour autant infliger une perte substantielle à la pêcherie. Un enseignement majeur résultant de ce travail est que cette approche résulte dans l'acquisition de données et le développement de mesures de gestion antérieurement au plein développement de la pêcherie et d'une méthode qui permet aux décideurs d'accepter facilement les mesures de gestion et d'ajuster ces dernières quand un problème apparaît. Un défi important reste à relever, celui de comment rendre compte du changement de statut des stocks et de l'écosystème et des rôles respectifs des pêcheries et du changement climatique dans ces changements pour l'ensemble du Plateau de Kerguelen.

Key words. - Ecosystem based fisheries management - Kerguelen Plateau - Heard Island - Southern Ocean - Harvest strategy.

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Conservation and sustainable use of marine biodiversity in the vicinity of Heard Island and McDonald Islands (HIMI, Fig. 1) have been important goals for the Australian Government since 1980 when it signed the Convention on the Conservation of Antarctic Marine Living Resources (hereafter termed ‘the CAMLR Convention’ while the associated Commission has the acronym CCAMLR). The Exclusive Economic Zone (EEZ) around the Australian Territory of Heard Island and McDonald Islands was initially declared in 1979 as part of the Australian Fishing Zone (AFZ), later becoming the EEZ in 1994 (see Welsford *et al*., 2011b for the history of jurisdictions around HIMI). The Territory and EEZ fall within the CAMLR Convention Area (primarily in Statistical Division 58.5.2).

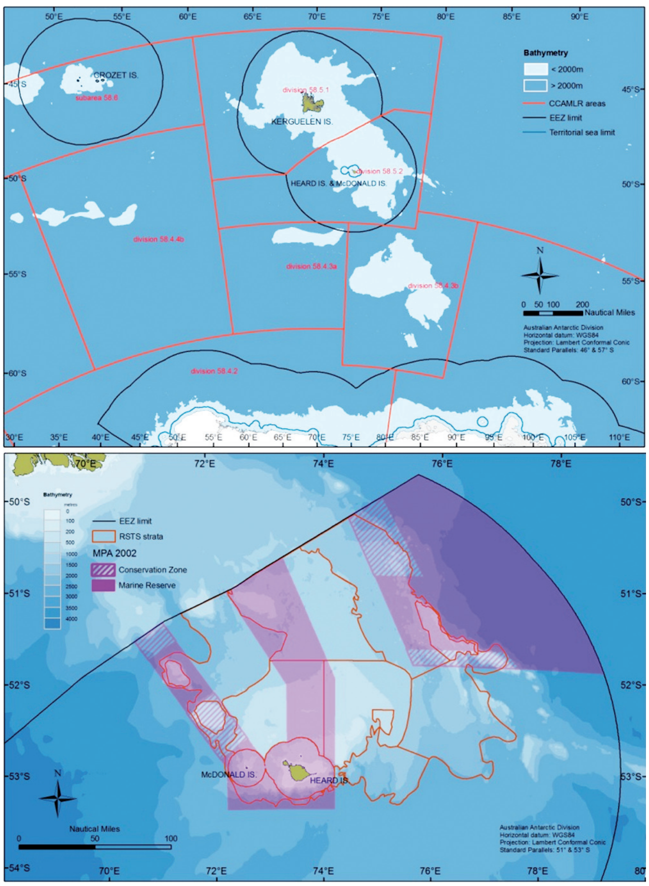

Figure 1. - Maps showing the Australian Territory of Heard Island and McDonald Islands (HIMI) in the Indian Sector of the Southern Ocean. Top panel: The greater Kerguelen Plateau, the northern portion of which has emergent islands at HIMI and, further to the north, the Kerguelen Islands within the Terres Australes et Antarctiques Françaises. The Kerguelen Plateau falls almost entirely within the area governed by the Convention for the Conservation of Antarctic Marine Living Resources (red lines indicate CCAMLR statistical subareas and divisions). Light blue indicates the areas shallower than 2000m. Bottom panel: Bathymetry in the HIMI area overlaid with key strata (red lines) for the annual random stratified trawl survey, the HIMI Marine Reserve (solid purple areas) and the HIMI Conservation Zone (striped purple areas). Data for the maps were provided by the Australian Antarctic Data Centre. Bathymetric data are from “Centenary Edition of the GEBCO Digital Atlas”, 2003, published on behalf of the Intergovernmental Oceanographic Commission and the International Hydrographic Organization as part of the General Bathymetric Chart of the Oceans; British Oceanographic Data Centre, Liverpool. The Antarctic coastline data are from the Antarctic Digital Database version 5.0 © Scientific Committee on Antarctic Research 1993-2006.

The current policy and legal framework governing HIMI has evolved since that time and the adoption of the Antarctic Marine Living Resources Conservation (AMLRC) Act in 1981, which was the legislation implementing the Convention in Australian law (Patterson *et al*., 2010). Research and initial stock assessments for the region were developed in a manner consistent with the need to resolve issues for Southern Ocean species that had become evident in CCAMLR (see Constable *et al*., 2000 for review).

Fishing by Australian companies in the HIMI region began in 1997 (Patterson *et al*., 2010). By that time, Australian domestic policy had embraced ecologically sustainable development (ESD) for fisheries (CoA, 1992) and Australia’s Oceans Policy was in the process of being developed, which had followed a number of important ocean-oriented policy and scientific activities through the 1990s (Vince, 2004) and was adopted in 1998[1]. This led to consistency between domestic policy and the objectives, outcomes and directions of CCAMLR. As a result, Australia has, to date, chosen not to invoke the mechanism to exclude HIMI from decisions of CCAMLR, even though it has the power to do so using the mechanism known as “the Chairman’s Statement” (Patterson *et al*., 2010).

Aside from the AMLRC Act 1981, Australia has two other primary pieces of legislation governing activities in the HIMI region with respect to conservation and fisheries - the Fisheries Management (FM) Act 1991 and the Environment Protection Biodiversity Conservation (EPBC) Act 1999. These provide the legislative foundations for ecosystem-based fisheries management (FM Act), conservation of marine biodiversity (EPBC Act), such as through marine protected areas and the management of threatened, endangered and protected (TEP) species (EPBC Act)[2].

The EPBC Act was also designed to have a regulatory function for ensuring the ecological sustainability of fisheries. To this end, all Commonwealth fisheries are required to be strategically assessed for compliance with the requirements of the EPBC Act. The separation of the implementation of the EPBC and FM Acts has been achieved through

[1] Documentation on Australia’s Oceans Policy is available at www.environment.gov.au/coasts/oceans-policy/index.html.

[2] The primary agencies responsible for administering these three Acts are the Australian Antarctic Division, Australian Fisheries Management Authority and the Commonwealth Departments of Foreign Affairs and Trade; Sustainability, Environment, Water, Population and Communities; and Agriculture, Forestry and Fisheries.

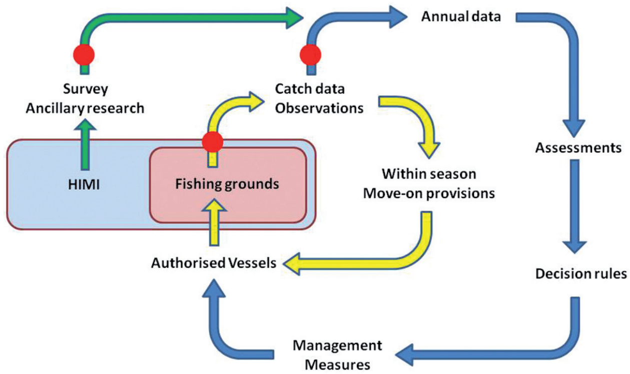

Figure 2. - Diagram of the management system at Heard Island and McDonald Islands showing the within season actions governing the behaviour of the vessels (yellow arrows), the annual submission of data from the fishery along with the process of assessments, the use of pre-agreed decision rules for determining catch limits, and the implementation of management measures through the Australian Fisheries Management Authority (blue arrows), and the stock surveys and other research on the HIMI marine ecosystem that will contribute to the annual process (green arrows). Red dots indicate important quality control and compliance check points.

the establishment of the Harvest Strategy Policy (DAFF, 2007). This policy identifies when management of a fish stock switches from the application of ecosystem-based fisheries management (EBFM) principles from the FM Act to the application of conservation requirements for species considered to be threatened or endangered.

This evolving marine policy, legal and regulatory framework within Australia, combined with its international obligations, has provided a strong foundation for achieving the goals for marine resources management and biodiversity conservation in the region. A significant factor in achieving such an approach is the implementation of scientific research and assessments before the fisheries were even mooted along with subsequent complementary development of the science and management methods, and governing procedures including mechanisms for stakeholder input, before the fisheries were fully developed.

The primary elements of the approach can be summarised as i) the precautionary approach to setting catch limits for target species, ii) a strategy for managing bycatch in the fisheries, notably mitigation of seabird mortality and minimising the bycatch of finfish species, iii) spatial management of activities to conserve representative areas of marine biodiversity in the region and to avoid fishing causing significant harm to benthic habitats, iv) mitigation of indirect effects of fisheries on food webs, and v) elaboration of approaches to adjust fishing in the event of climate change or other impacts on the ecosystem.

Here, we detail each of the elements of the approach aimed at achieving the objectives of conservation and sustainable use of marine biodiversity in the HIMI region. Throughout the discussion, we illustrate the scientific principles and research used to facilitate achieving the objectives. We also discuss the ongoing evaluation and refinement of management and research into the future.

Managing targeted fisheries

Aside from the unregulated international trawl fishing activities occurring in the region in the 1970s, substantial regulated fishing did not occur until 1997 (Duhamel and Williams, 2011). Prior to this, in 1990, 1992 and 1993, three large scale benthic trawl surveys were undertaken on the plateau in the HIMI EEZ for the purposes of identifying and assessing the abundances of potentially harvestable stocks before harvesting would be undertaken in regulated Australian fisheries (Williams and de la Mare, 1995). They found two species in harvestable quantities – Patagonian toothfish (*Dissostichus eleginoides* Smitt 1898) and mackerel icefish (*Champsocephalus gunnari* Lönnberg 1905).

An important advantage of this approach meant that assessments of sustainable catch could be undertaken prior to fishing. Measures could then be set in place that were highly likely to keep the stock around target levels and to have only a low chance of becoming depleted. This was the precautionary approach adopted in CCAMLR (see Constable *et al*., 2000 for review of the history and implementation; Constable, 2011) and later endorsed in the UN FAO's precautionary approach for fisheries (FAO, 1996).

The expectation in the precautionary approach is for catches to increase as knowledge improves, while maintaining the same level of precaution; improved knowledge may also result in shifts in data requirements, assessment methods or means by which harvest strategies are approved. The precautionary approach involves (i) acquiring data to assess the status and productivity of the stock, (ii) having a method to assess the impacts of a nominated harvest strategy (e.g., a total allowable catch) on the stock (and ecosystem) in the future and (iii) establishing rules for deciding on which harvest strategy to adopt in order to achieve the sustainability objectives while taking into account errors and uncertainties in the assessment of stock status and the parameters used in assessing impacts of the future harvest strategy (Fig. 2). These three elements are reviewed for mackerel icefish and, particularly, Patagonian toothfish to assess how they have evolved at HIMI. This assessment is followed by a review of the evolution of catch limits in the fishery, the impacts that different factors may have had on those catch limits, and, notably, whether the precautionary approach has assisted in the long term sustainability of these fisheries.

Assessing stock status and productivity

In addition to the first three groundfish surveys in the early 1990s, status of stocks on the plateau around HIMI have been monitored annually with random stratified trawl surveys in waters less than 1000 m depth conducted since

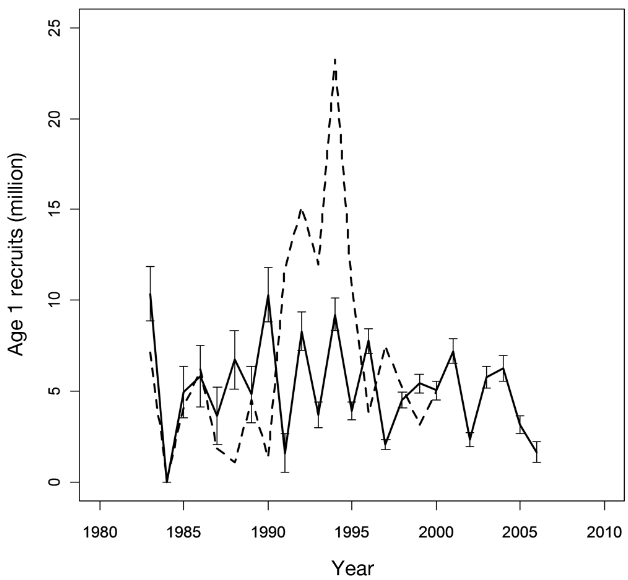

Figure 3. - Time series of Age 1 recruits of Patagonian toothfish in the vicinity of Heard Island. Solid line is the estimates of recruitments (+SE) from the 2009 integrated stock assessment using CASAL (natural mortality M = 0.155). Dashed line is the estimates of recruitment for M = 0.165 in 2004 derived from mixture analyses of length densities from trawl surveys (see text for details).

1997. The strata were based on those identified in the early surveys but were refined with more data and with a better understanding of the areas of concentration of the target species. The current design was consolidated following a review of the efficacy of the design in 2004 to facilitate surveys of recruits of Patagonian toothfish combined with assessments of the populations of mackerel icefish (Candy *et al*., 2004; Welsford *et al*., 2011a). In addition to these surveys, two observers have been deployed with every fishing vessel since the beginning of the fishery to record the composition of the catch and other biological information important for the management of the fishery, administer a mark-recapture program and undertake research that would contribute to a better understanding of the ecology of the ecosystem.

Patagonian toothfish is distributed across the Kerguelen Plateau, with juveniles occurring in shallower water (< 1000 m) than adults (see Welsford *et al*., 2011a for review). In contrast, mackerel icefish appears to occur in two stocks both of which are generally found in water shallower than 300 m near to Heard Island on the shallow plateau and at Shell Bank (de la Mare *et al*., 1998).

For Patagonian toothfish, stock status has been derived in three different ways since total allowable catches have been determined. In 1995, the stock was considered to be in a pre-exploitation state and the estimates of biomass from the three surveys in the early 1990s (Williams and de la Mare, 1995) were used as the population biomass estimates of B_0 (estimate of total biomass prior to fishing) in the CCAMLR decision rules.

In 1996, the composition of the survey catches was shown to be primarily of juvenile fish. Estimates of cohort strength were used as the basis for projecting possible stock trajectories (SC-CAMLR, 1995; Constable and de la Mare, 1996), from which a distribution of plausible biomasses of spawning stock, along with its status relative to the pre-exploitation state were derived. This process involved estimating abundance from the haul data of each length class based on the delta-log-normal approach of de la Mare (1994a), an important method for overcoming bias in survey data where there are many hauls with zero catch. These estimates of abundance of length classes were then used to estimate the abundance of the different age cohorts using maximum likelihood methods, taking account of the error distributions surrounding the length class estimates (mixture analyses now known as CMIX[3]) (de la Mare, 1994b). Repeat surveys meant that a number of cohorts had repeat observations, which enabled better estimation of cohort strength, a feature that would strengthen the value of the time series of surveys to come. The results were then used to estimate a mean and coefficient of variation (CV) of a log-normal recruitment function, taking account of the error in the estimates of cohort strength and the need to correct cohorts to a specific age of recruitment (age 4 in this case). This function became the basis for determining the pre-exploitation median spawning biomass (see SC-CAMLR, 1995; SC-CAMLR, 1996 for the details of the approach).

The estimates of cohort strength meant that projections could include a time series of year class strengths (with error) and the removal of catches. A key uncertainty in this approach was the actual biomass of the spawning stock at the beginning of the time series of observed cohorts. Similarly, the recruitment of a number of cohorts was not observed because of the absence of surveys in a number of years. The uncertainty in stock status for a given year was captured in the following steps, implemented in the Generalised Yield Model (GYM) (see Constable and de la Mare, 1996 for a full description): i) randomly determine the initial age structure (1985) from the log-normal recruitment function, ii) project through the observed series of cohorts to the present and removing known catches, iii) the cohort strength in a given year was drawn from a log-normal error distribution based on the estimate of cohort strength and its error, iv) in years for which the cohort strength was not estimated, the abundance of recruits was drawn randomly from the recruitment function, and v) this process was repeated a large number of times using Monte Carlo methods to integrate across all the errors in the estimates.

[3] The CMIX software is available at www.antarctica.gov.au/science/southern-ocean-ecosystems/fish-and-fisheries/conservation-and-management/cmix

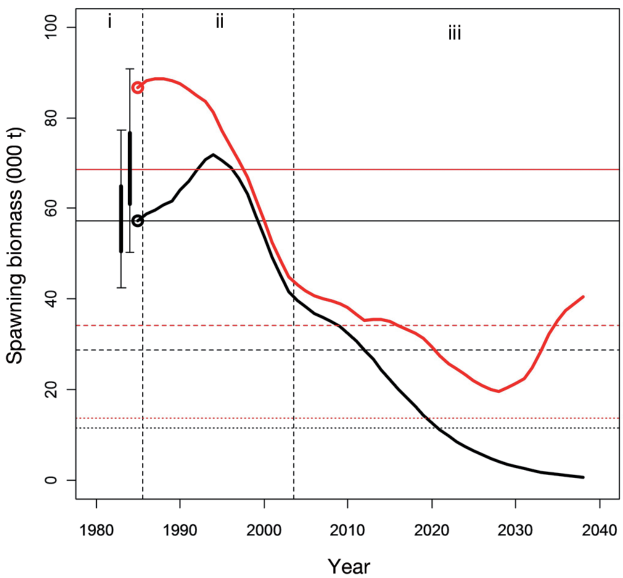

Figure 4. - Two projections (black & red) of the spawning biomass of Patagonian toothfish at HIMI from the 2004 assessment of catch limits. The vertical lines separate three periods: (i) the 'pre-exploitation' period, prior to 1986 of the known period of recruitments and fishing, (ii) the known period between 1986 and 2004, including recruitments and fishery catches, and (iii) the projection period over which time the possible future catch limits are assessed against the decision rules. The differences between the projections are the starting age structure (and spawning biomass), the natural mortality rate and the time series of recruitments in the future. The box plots on the left indicate the expected natural variation in spawning biomasses prior to exploitation. Horizontal lines indicate the status of the spawning stock in each trial relative to the median pre-exploitation spawning stock – solid line is the pre-exploitation median level (status = 1.0), dotted lines indicate 0.5 of the median level for each trial, and dashed line indicates 0.2 of the median level; these correspond to the reference points in the CCAMLR decision rules. The black trial indicates a trial where the stock became depleted whereas the red trial is an example where the stock came close to the target level by the end of the projection.

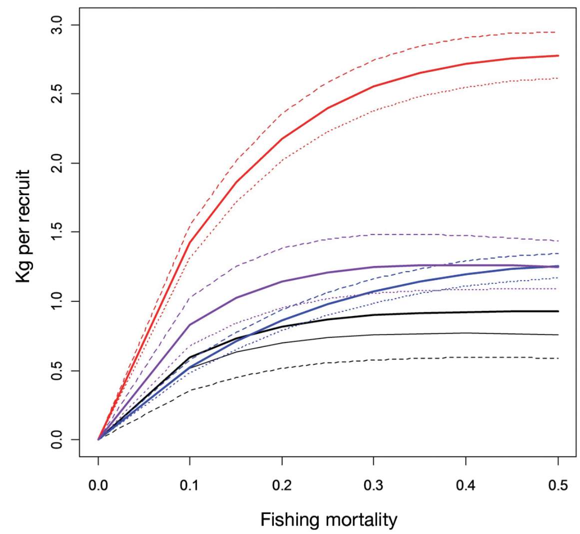

Figure 5. - Yield per recruit curves for Patagonian toothfish in the vicinity of Heard Island based on parameters at different times in the assessment history – 1996 (red curves), 1999 (blue curves), 2001 (purple curves) and 2009 (black curves). For 1996-2001, curves represent the ranges of natural mortality in the assessments – lower bound (dashes), mean (solid), upper bound (dots). In 2009, the bold line represents longline selectivity, the thin solid line represents the early trawl selectivity 1997-2006, and the dashed line represents the later trawl selectivity 2006-2009.

Further, the parameters used in the projections, most notably natural mortality (M), may have uncertainty as well. The process was repeated using Monte Carlo methods to integrate across the uncertainty in these parameters. This meant that for each trial the estimate of the pre-exploitation median spawning biomass would differ because of the different set of natural mortality and other parameters. Thus, stock status would be estimated within each trial relative to that value for the trial. This process is illustrated in Figures 3 and 4 which show, respectively, the time series of recruitments estimated in 2004 and two example projections from the 10001 Monte Carlo projections to determine the catch limit in that year. Figure 4 illustrates how uncertainty in initial spawning biomass relative to the pre-exploitation median, mean recruitment and variability, natural mortality and other parameters can yield different estimates of stock status even though the time series of spawning biomasses over the known period are approximately the same.

A difficulty with the early procedure for estimating abundances of recruits is estimating cohort strength from each survey independently and then later combining them rather than using successive surveys in a single estimation procedure. An important factor in estimating cohort strength is the ability to observe each class (vulnerability) in the survey design. The evolution of the survey design to routinely include deeper water from 2004 onwards was to satisfactorily observe juvenile age classes despite interannual variation in the distribution of juveniles across the plateau. Surveys prior to this consolidation had different selectivities of the older juveniles (greater than eight years old) leading to considerable variability in the estimates of abundance of a cohort if the change in selectivity for that cohort was not taken into account.

Following the introduction of CASAL (Bull *et al*., 2005) into CCAMLR (Dunn *et al*., 2004), an integrated assessment using all available data from the fishery and the surveys was established for this stock in 2006 (Candy and Constable, 2008). This assessment now uses the survey data as well as length composition data from the fishery. It also facilitated the estimation of the selectivity at age for different survey designs. As a result, cohort strengths are now better estimated; Figure 3 shows the time series of Year 1 recruits estimated in 2009. Mark-recapture data is not yet used because of its localised nature to date. Such data are expected to be used in the future as the spread of tags across the area improved.

The biological and fishery selectivity parameters used

Table I. - Evolution of key parameters used in assessments of catch limits of Patagonian toothfish at HIMI. GYM is the Generalised Yield Model (Constable and de la Mare, 1996). CASAL is the C++ algorithmic stock assessment laboratory (Bull *et al*., 2005). LAA = length at age vector. ALK = Age Length Key. CV = coefficient of variation. A_{m50} = age at 50% maturity. L_{m50} = age at 50% maturity.

Assess-ment year	Catch limit (000 t)	Model	Parameters													Comments
			Length-weight		Length at age			Natural mortality	Recruitment				Selectivity		Maturity	
			a E-05	b	k	L_∞ (cm)	t_0	M	Age	Mean (E6)	CV	Survey series	Fleets	Fully selected age classes	Ogive	
1996	3800	GYM	2.5	2.8	0.088	170.8	0	0.12-0.2	4	2.359	0.442	1990, 1993	Trawl only	6-7	A_{m50} = 9 yrs	Majority of parameters derived from South Georgia population. Recruitment mean and CV based on surveys at HIMI prior to the fishery
1997	3700															IUU and legal catch included. Other parameters unchanged.
1998	3690															IUU and legal catch estimates updated. Other parameters unchanged.
1999	3585		0.42	3.206	0.0414	1946	-1.797	0.083-0.124		4.714	1.182	1990, 1993, 1999		6-8	A_{m50} = 15 yrs	Growth, selectivity and maturity parameters revised on the based on samples collected at HIMI. M revised to reflect changed estimate of k. Recruitment parameters include new survey data. IUU and legal catch estimates updated.
2000	2995									4.143	1.296	1990, 1993, 1999, 2000				Recruitment parameters include new survey data. IUU and legal catch estimates updated.
2001	2815				0.029	246.5	-2.46	0.13-0.2		3.907	1.021	1990, 1992, 1993, 1999-2001	Trawl, IUU longline	Trawl: 6-10 IUU Longline: 8-14	L_{m50} = 930mm	Growth and maturity parameters revised on the based on samples collected at HIMI. M revised to reflect changed estimate of K. Recruitment parameters include new survey data and 1992. IUU and legal catch estimates updated. Selectivities adjusted for trawl and IUU longline catches.
2002	2879									4.018	0.975	1990, 1992, 1993, 1999-2002				Recruitment parameters include new survey data. IUU and legal catch estimates updated.
2003	2873									3.991	0.921	1990, 1993, 1999, 2001-2003				Recruitment parameters include new survey data, and excluded 1992 and 2000. IUU and legal catch estimates updated.
2004	2787									4.202	0.846	1990, 1993, 1999, 2001-2004				Recruitment parameters include new survey data. IUU and legal catch estimates updated.

Table I. - Continued.

Assess-ment year	Catch limit (000 t)	Model	Parameters: Length-weight a E-05	Length-weight b	Length at age k	Length at age L_∞ (cm)	Length at age t_0	Natural mortality M	Recruitment Age	Recruitment Mean (E6)	Recruitment CV	Recruitment Survey series	Selectivity Fleets	Selectivity Fully selected age classes	Maturity Ogive	Comments
2005	2584				LAA			0.13-0.165		3.911	0.944	1990, 1993, 1999, 2001-2005				Recruitment parameters include new survey data. IUU and legal catch estimates updated.
2006	2427	CASAL			LAA with CV of 0.1				1	2.879		1990, 1992, 1993, 1999, 2001-2006	Multiple gear type and season combinations	Survey:5-7 Trawl: 5-10 Longline: 10-15	A_{m50} = 15 yrs	Move to CASAL enabled estimation of selectivity parameters for multiple fleets. All surveys included with catchability (q) in Survey Group 1 (2001, 2002, 2004-2007) set to 1, and others fleet qs estimated. Maturity ogive converted to age-based. Process errors and effective samples sizes also estimated. IUU and legal catch estimates updated.
2007-08	2500									2.915	1.16	1990, 1992, 1993, 1999, 2001-2007				Recruitment parameters include new survey data. IUU and legal catch estimates updated. Effective sample size methodology refined.
2009	2550				ALK					2.705	0.6	1990, 1992, 1993, 1999, 2001-2009				Gear and season specific age length keys, with ageing error, applied to all fisheries. Recruitment parameters include new survey data. IUU and legal catch estimates updated.
																Natural mortality estimated from mark-recapture and other data.
[2009]								0.155								Natural mortality estimated from mark-recapture and other data.

in the assessments have varied since 1997 (Tab. I). As a result, the expectations surrounding the productivity of the stock has changed from a highly productive stock to one with a lower productivity, as evidenced in yield per recruit calculations based on the parameters used at different assessment years (Fig. 5). All key biological parameters have now been estimated – length at age (Candy *et al*., 2007), natural mortality (Candy *et al*., 2011) and the maturity ogive (Constable *et al*., 1999) .

Initially, the value for M for Patagonian toothfish was tied to an estimate of growth rate based on the premise that the ratio between M and the von Bertalanffy growth parameter k was a constant (Charnov, 1993). A difficulty with this approach is whether k and M reflect fixed biological attributes of the species. The evolution of the life history of a species may result in correlation of these parameters that is generally retained over time. However, the exact ratio relevant to these projections will be dependent on current ecological status of the food web (prey availability and predator abundance), which may now be very different to the period of greatest evolutionary pressure (e.g., on foraging tactics and predator avoidance, and sexual selection), and the degree of interannual variability in the relationships between species. The estimation of these parameters has now been undertaken independent of a theoretical ratio, thereby avoiding these assumptions.

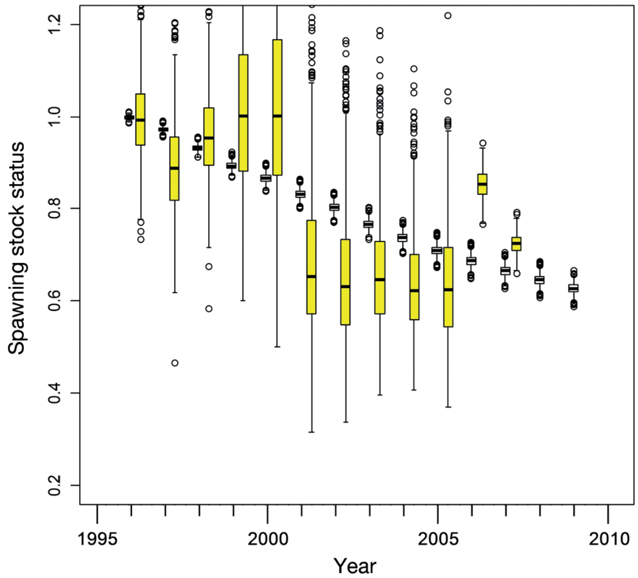

Figure 6. - Box plots of stock status of Patagonian toothfish at Heard Island and McDonald Islands based on the 2009 assessment with M=0.155 (clear boxes) and the accompanying 'current' stock status from each assessment year, i.e. the status of the stock in the year of the assessment estimated by the assessment of that year (yellow boxes). 'Current' status was estimated for each year in the period 1996 to 2005 using external assessments of numbers recruits and uncertainty across parameters and initial spawning stock abundance was integrated using projections in the Generalised Yield Model. Projections included the history of fishing. Integrated assessments using CASAL have been undertaken since 2006 and distributions of spawning stock biomass were derived, in this instance, from multivariate normal resampling of the estimated parameters. No assessment was done in 2008.

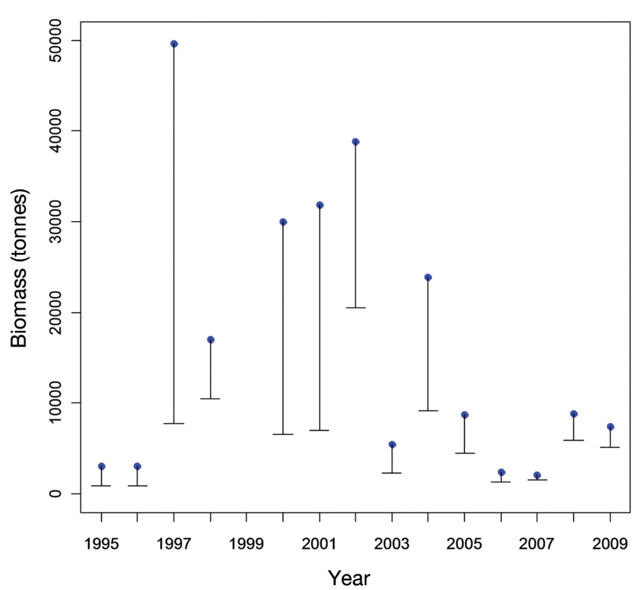

Figure 7. - Mean (circle) and lower 95 percentile (horizontal bar) of the biomass of mackerel icefish derived from trawl surveys conducted at Heard Island and the McDonald Islands. The lower 95 percentile estimate of biomass is used in the short term projections to determine precautionary catch limits.

Figure 6 shows how the estimates of stock status has changed over the course of the assessments as a result of (i) changes in the parameters, (ii) increasing number of surveys giving repeat observations of cohorts as well as a longer time series of cohorts, and (iii) using the integrated assessment methods to estimate the selectivity functions for the surveys as well as the fishery. In the figure, the 'current' stock status from each assessment year is compared with the time series of stock status from the 2009 assessment. It also shows how uncertainty in stock status has progressively been reduced. Currently, the assessment indicates that the Patagonian toothfish stock at HIMI is around 0.63 of the median pre-exploitation level.

The population dynamics, biology and ecology of mackerel icefish are very different to Patagonian toothfish. Icefish live in shallow water for all of their lifecycle, and therefore their abundance can be directly monitored using trawl surveys. In addition, the sporadic nature of its recruitment means that cohorts can be relatively easily monitored through time (de la Mare *et al*., 1998; Williams *et al*., 2001). Figure 7 shows the dynamics of mackerel icefish on the plateau adjacent to HIMI. The Shell Bank population is only in low abundance, is closed to fishing, and is not surveyed as regularly as the plateau stock.

Mackerel icefish was likely to have been targeted across the Kerguelen Plateau, including the submarine banks around HIMI, by Soviet fishing operations in the 1970s (Pschenichnov, 2011). It is not clear to what extent the stocks in the region have recovered from that time, if at all. The apparent cyclical nature of recruitment (occurring approximately every three years) is different to the overlapping generations in the rebuilding stock at South Georgia (SC-CAMLR, 2010b). A possible consequence of historical fishing may be that the current strong cohorts are behaving as a single cohort population because three years is the time to maturity. Icefish are prey of Fur seals (*Arctocephalus* spp.) and are likely to suffer considerable mortality by age four when they largely disappear from the stock, and this dynamic needs to be factored into the management strategy for the stock.

The biology of mackerel icefish at HIMI was extensively reviewed in de la Mare *et al*. (1998) and by the CCAMLR Working Group on Fish Stock Assessment (SC-CAMLR, 2001b). The biological parameters for icefish have been estimated (Tab. II). There is evidence for density-dependent growth (Williams *et al*., 2001), which is currently being reviewed for incorporation into the stock assessment as it is likely to be important for understanding the impacts of harvest strategies on the future productivity of cohorts.

Assessing impacts of future catches and setting catch limits

Management strategies for Patagonian toothfish and mackerel icefish use decision rules to determine annual

Table II. - Evolution of key parameters used in assessments of catch limits of mackerel icefish at HIMI. GYM is the Generalised Yield Model (Constable & de la Mare, 1996). Modified krill yield model is from Butterworth *et al*. (1992; 1994). Mathcad is software by Mathsoft.

Assessment year	Total Allowable Catch	Model	Parameter						Comments
			Length-weight		Size at age			Natural mortality	
			a	b	k	L_∞ (mm)	t_0	M	
1994-1996	311	Modified krill yield model	–	–	0.370	390	0	0.3-0.5	Key parameters derived from Kerguelen stocks. Catch limit based on long term projections, with biomass from surveys in 1990, 1992, 1993.
1997	900	GYM	2.629E-10	3.515	0.410	411	0.571	0.3-0.64	Key parameters revised from samples collected at HIMI. t_0 adjusted to account for hatching date in November. Catch based on long term projections of cohort biomass from 1990, 1992, 1993 and 1997 surveys.
1998	1160	Mathcad					0.234	0.4	M revised to mean of previous values. Catch based on short term projections of cohort biomass from 1998 survey. Fishery on Shell Bank closed.
1999	916								Catch based on short term projections of cohort biomass from 1998 survey.
2000	1150								Catch revised based on short term projections of cohorts in 2000 survey.
2001	885				0.323	457	0.358		Growth revised based on expanded cohort progression data. Catch revised based on short term projections of cohorts in 2001 survey.
2002	2980								Catch revised based on short term projections of cohorts in 2002 survey.
2003	292	GYM					0.027		Catch revised based on short term projections of cohorts in 2003 survey, implemented in the GYM.
2004	1864						0.275		Adjustment made to growth model to better account for cohort growth. Catch revised based on short term projections of cohorts in 2004 survey.
2005	1210								Catch revised based on short term projections of cohorts in annual surveys, 2005-2009.
2006	42								
2007	220								
2008	102								
2009	1658								

catch limits (total allowable catches-TAC). These rules are based on target and limit reference points for the stocks and the manner in which a TAC is chosen to take account of uncertainty in order to achieve ecological sustainability (see Constable *et al*., 2000 for review).

The decision rule for Patagonian toothfish was adapted by CCAMLR from its decision rule for krill. In 1996, the rule only adjusted the target level of escapement to 50% rather than 75%, the latter escapement being for important prey species. In 1997, the decision rule was adjusted further to seek the long-term annual catch that complied with the rule (Constable and de la Mare, 1996). The agreed harvest strategy was to have a constant catch over a long period, 35 years in this case, in order to minimise the variation in catch to the fishery. Thus, the current rule as applied in CCAMLR is: i) [depletion criterion] choose *Catch 1*, so that the probability of the spawning biomass dropping below 20% of its pre-exploitation median level over a 35-year harvesting period is 10%; ii) [escapement criterion] choose *Catch 2*, so that the median toothfish escapement in the spawning biomass over a 35-year period is 50% of the pre-exploitation median level; and iii) select the lower of *Catch 1* and *Catch 2* as the yield.

The general approach is to use Monte Carlo simulations to integrate across statistical errors and 'process'

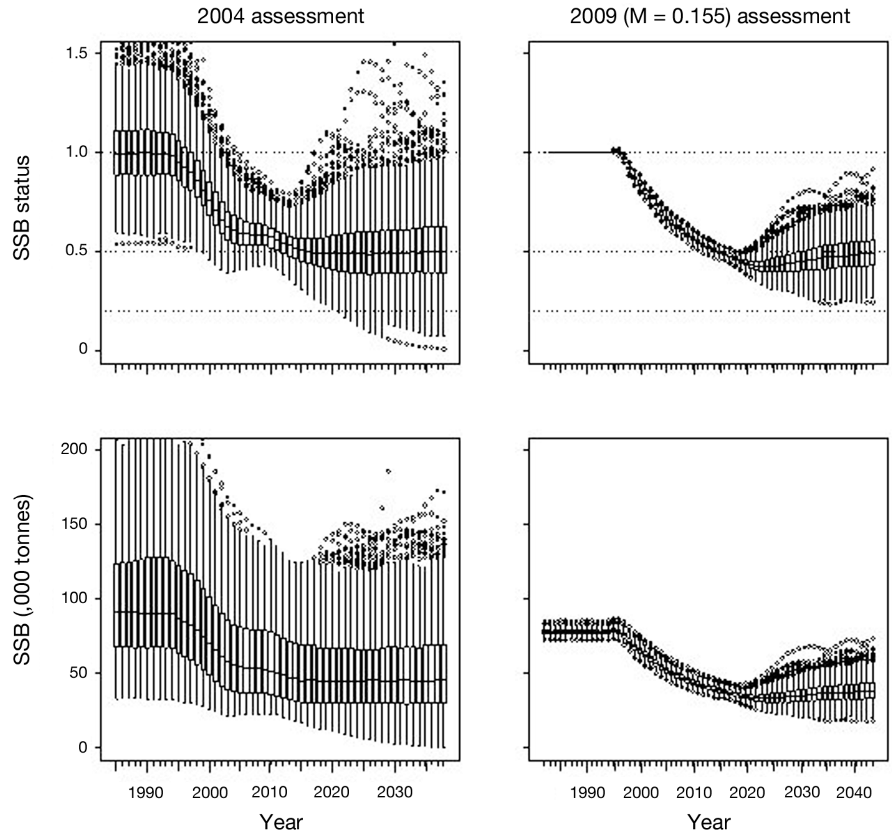

Figure 8. - Projections of spawning stock biomass and spawning stock status of Patagonian toothfish in assessments of catch limits at HIMI for assessment years of 2004 (using the Generalised Yield Model) and in 2009 (M = 0.155) using CASAL. Projections over the known period include estimates of recruitment as well as removal of the fishery catches. Projections into the future are for catches of 2 787 t in 2004 and 2 550 t in 2009. Stock status is used to determine the catch that complies with the CCAMLR decision rule for toothfish, the maximum catch that results in both (i) the median status (relative to the median pre-exploitation spawning biomass) at the end of the projection after 35 years is greater than or equal to 0.5, and (ii) the proportion of trials that result in the spawning stock status being less than 0.2 at any time in the projection is less than or equal to 0.1.

(model) uncertainty as described above to assess the impacts on the stock of different long-term annual catch limits and to find the catch limit that will satisfy the decision rule. Process uncertainty is the uncertainty in the actual model representing fish stock and fishery dynamics as well. The application of the rule to the assessment is illustrated in figure 8 with box plots showing the uncertainty in spawning biomass and stock status prior to the known period, during the period in which year class strength is estimated and the fishery is taking catches, and then over the projection period of 35 years when the catch limit is assessed.

The current assessment of the TAC for Patagonian toothfish does not integrate across all the uncertainty. For example, uncertainty in M is not factored into the CASAL assessment. This is because M has not been able to be estimated reliably in the integrated assessment of stock status. Recent work by Candy *et al.* (2011) has estimated M externally to the CASAL assessment based on the mark-recapture data. Incorporating this estimate with its uncertainty is the next step. One approach to do this could be to do assessments and projections for values of M across the range of M and then weight the probability distributions for depletion and reaching the target by the statistical weight of that value of M from the error distribution.

The decision rule for mackerel icefish evolved from attempting to apply the CCAMLR decision rule for toothfish but with a prey escapement level of 75%. However, the highly variable recruitment and, therefore, abundance of the stock meant that it failed to meet the depletion criterion even in the absence of fishing (de la Mare *et al.*, 1998). A short-term assessment rule based on fishing mortality (F) was developed (*ibid.*) to directly achieve the prey escapement target level of 75% without having to be concerned about future potential for depletion arising from recruitment variability, i.e., to choose the fishing mortality which would result in a probability of no more than 0.05 that the spawning stock after fishing would be less than 75% of the level that would have occurred in the absence of fishing.

Catches are determined over a two year period from the last survey of the stock structure and biomass. The decision rule is met by numerically finding the F that would satisfy the rule. The projected catch is applied to the lower one-sided 95% confidence bound of the estimate of abundance (Fig. 9).

Evolution and performance of the fishery

The fishery at HIMI has developed substantially since 1997 (Fig. 10). The most important target species is Patagonian toothfish but mackerel icefish can be important in years when it is in great abundance and sufficiently aggregated to target by trawling. The evolution of the Patagonian toothfish fishery, including the period of high levels of illegal fishing,

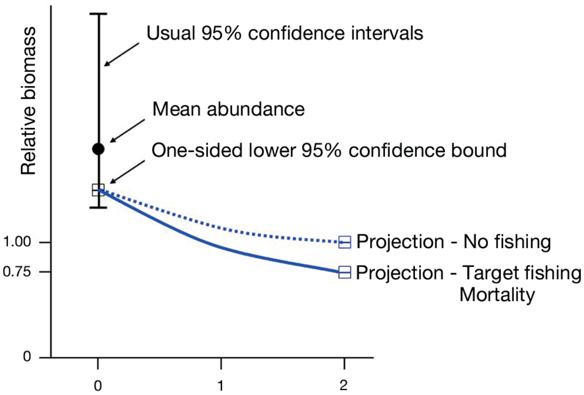

Figure 9. - Illustration of the decision rule for mackerel icefish where a survey is required to estimate the age structure of the stock and the total biomass. The lower one-sided 95% confidence bound is used to project the stock forward to determine the catch that will reduce the stock at the end of two years to no less than 75% that it would have been at that time in the absence of fishing.

provides a useful case study for assessing the performance of the precautionary approach used at HIMI.

The precautionary approach is intended to ensure that the risk of failure to meet the objectives remains the same as the fishery expands; critical uncertainties are expected to be identified and resolved before catches are increased. Results of early work can be used to identify how long it might be before critical issues of stock status might arise. They can then be used to trigger research and actions that may circumvent the need to reduce catch limits if done in time. As the uncertainties are reduced and/or additional management arrangements are set in place to avoid emerging problems, catches may be able to be increased while still maintaining the risk of failure at or below the acceptable level.

At HIMI, the uncertainties in productivity, fishing pressure and recruitment dynamics have been substantially reduced. The research to date has revealed that the stock is not as productive as originally thought; high levels of illegal fishing impacted on the sustainability of the legal fishery and recruitment dynamics are more variable than perhaps expected for such a long-lived species (50+ years). It has also shown that the legal fishery has a changing relationship with the stock and that yields might increase with changes in fishing strategies. What impact have these factors had on the fishery and what might be learnt for the future?

Effects of changes in understanding of productivity and recruitment dynamics

The changing catches in the legal fishery reflect the changes in the catch limits for the region. The initial increases in catch limits were largely due to some large cohorts dominating the recruit surveys coupled with productivity parameters that were higher than what have now been estimated directly; the original growth parameters were not from toothfish in the region.

The decline in catches in more recent years reflects revisions of both productivity and estimates of abundances of new recruits and the spawning stock. The level of uncertainty in early years surrounding productivity and the status of stocks is shown in figure 6. The reduction in uncertainty is clearly demonstrated in figure 3, which shows the improved estimates of recruitment, and in figure 8, which shows the difference in precision between the old assessment methods and the recent integrated assessments.

Effects of fishing history and changing selectivities on future catches

The most recent assessment in 2009 has shown that the Patagonian toothfish fishery at HIMI has four main components historically – early trawl (1997-2006), which captured juvenile fish ranging to age classes just becoming mature,

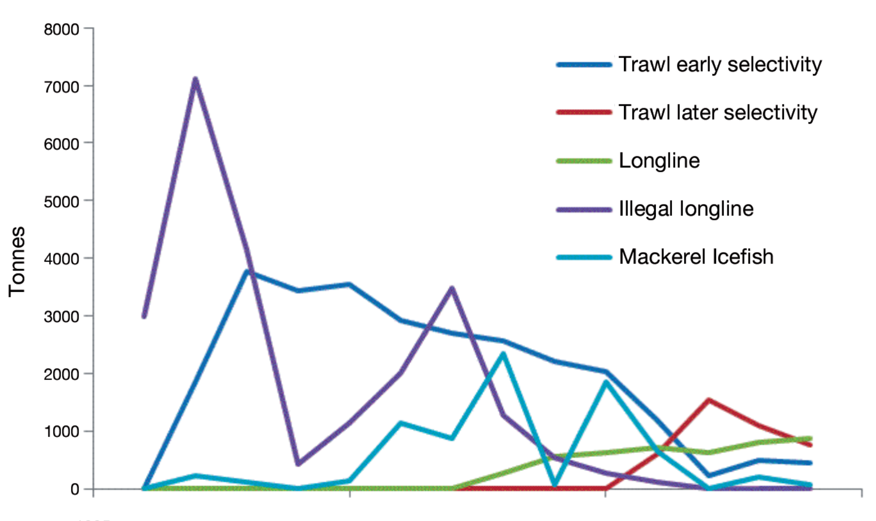

Figure 10. - Time series of catches of Patagonian toothfish and mackerel icefish at Heard Island and McDonald Islands since the beginning of the fishery in 1996. Four components of the fishery for Patagonian toothfish are shown – the legal trawl with selectivity of the early years 1997-2006, the legal trawl with selectivity of the later years 2006-2009, the legal longline which has operated since 2003 and the illegal longline, which began prior to the major development of the legal fishery.

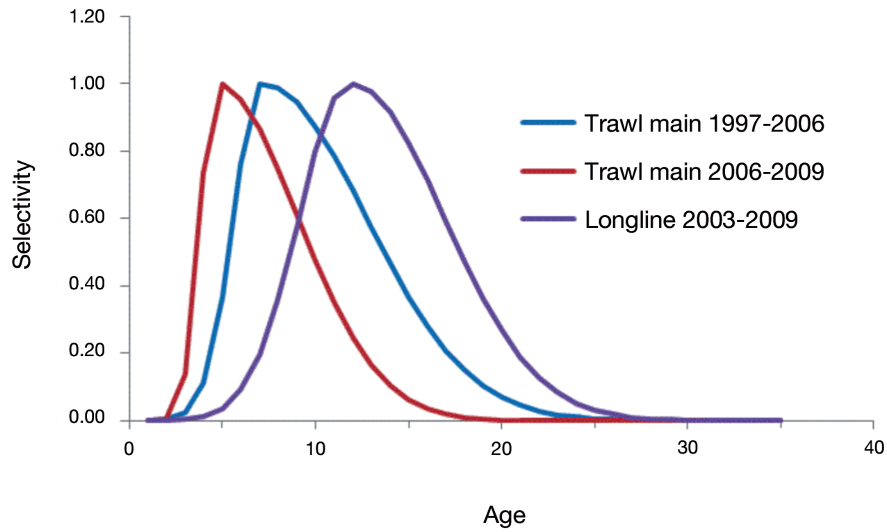

Figure 11. - Selectivity at age of Patagonian toothfish in the fishery at Heard Island and McDonald Islands. Trawl gear has been the primary fishing method but the selectivity can be divided between two periods: (i) 1997 -2006, and (ii) 2006-2009. Integrated Weighted Longline gear has been used since 2003. The selectivity of illegal longline operations is assumed to be the same as that for the legal longline fishery.

later trawl (2006-2009), which has been capturing younger fish than the earlier trawl, longline (2003-2009) and illegal longline. The ages at which fish are vulnerable (selectivities) to the trawl and longline methods are shown in figure 11. The difference in selectivities between the early and later trawl periods is because of a reduction in size of fish in the main fishing grounds. Trawling elsewhere in recent years shows a selectivity pattern similar to the early years in the main grounds. Longlining is undertaken with integrated-weighted lines for demersal fishing and is more widespread than trawl. It is assumed that the selectivity of illegal longline fishing was the same, even though the Spanish longline system was used by the illegal fleet.

The latest estimates of the productivity parameters, including the recruitment time series, can be used to assess whether the historical time series of catches has impacted on future catch potential; what have been the consequences of the precautionary approach to the fishery and to the stocks at HIMI? This question is addressed by evaluating, using the CCAMLR decision rule, the constant long-term annual yield (LTAY) under four scenarios: Scenario C1 – the log-normal recruitment function (mean and CV of recruitment) but no recruitment or fishing history, thereby integrating across uncertainty in numbers at age at the beginning of the projection; Scenario C2 – the recruitment function but with the known recruitment history 1983-2006 and including a catch history for 1997-2009 as the constant LTAY determined from Scenario C1 (this scenario forms the control for comparing the effects of the historical catch series on future catch potential); Scenario C3 – Scenario C2 but including the legal catch history for 1997-2009 in place of the LTAY, thereby enabling the effect of the legal catches on future catch potential to be evaluated as the difference of this outcome from Scenario 2, noting that uncertainty in age composition of the stock is greatest in the earlier years of the historical period; and Scenario C4 – Scenario C3 but including the illegal catch history as well, thereby enabling an assessment of the illegal catches on the future catch potential.

This assessment used the Generalised Yield Model (Constable and de la Mare, 1996) to undertake the projections over the known catch period and then forward for 35 years. It used parameter values from the 2009 assessment, including natural mortality of 0.155 yr^{-1}. The selectivity functions for the future fishery are those illustrated in figure 11. Results are shown in table III.

Clearly, the most important effect on the future potential catch from 2010 is the fishing selectivity. The longline strategy is likely to yield substantially more than the trawl strategy. The trawl strategy is best when it can retain the older ages in its catch (the early selectivity pattern). Continued harvesting with the current overall strategy, while ecologically sustainable, may result in a 20-25% loss of value to the fishery. Notably, the results for Scenario C1 indicate sustainable long term annual catch less than the catches early in the fishery.

The long-term annual yield following the known catch history (Scenarios C3 and C4) is approximately 5% less than a catch history consistent with the CCAMLR decision rule using the most recent productivity parameters (Scenario C2). The results indicate that the effect of the early higher exploitation rate is unlikely to have long-lasting implications (but see Management Strategy Evaluation below). However, this result may underestimate the impact of historical fishing, particularly the illegal activities, on the future because this analysis does not include a spawning stock-recruitment function; no provision was made in these scenarios for a decline of the spawning stock to impair recruitment but this should be investigated in future.

Table III. - Results of assessments of the maximum constant long-term annual yield (tonnes) that satisfies the CCAMLR decision rules for Patagonian toothfish at Heard Island and McDonald Islands, using the Generalised Yield Model, contrasting results for a) constant annual catches and b) constant fishing mortality (F). Projections were undertaken according to the methods used in assessment years 1996-2005, projecting over the known catch period, where appropriate, and forward for 35 years. Parameter values were from the 2009 assessment, including natural mortality of 0.155 yr^{-1}. The selectivity functions for the future fishery are those illustrated in figure 10. In order to pool the catch to make the analyses straight forward, the selectivity function for each year of the historical fishery was approximated as a weighted mean across the three fishery selectivities (weights were determined for each fishery in each year as the fishery catch divided by the yield per recruit for F = 0.1 yr^{-1}). Scenario C1 assessed the difference between the different selectivites on the future catch potential without influence of the known fishing catches or recruitment series. These used the mean recruitment and recruitment CV from the 2009 assessment. Scenario C2 examined the impact of the estimated year class strengths along with the long-term annual yield from Scenario C1 to act as a control for Scenarios C3 and C4. Scenarios C3 and C4 examined the effects of adding the legal fishery and then the illegal fishery to the historical period. Scenario F1 used the same parameters as in C1 but searched for the constant fishing mortality (in place of catch) that would comply with the CCAMLR decision rule.

a) Scenario		Trawl selectivity 1997-2006 Catch (tonnes)	Trawl selectivity 2006-2009 Catch (tonnes)	Longline selectivity 2003-2009 Catch (tonnes)
C1	Log-normal recruitment function	2445	2025	2775
C2	C1 + YCS 1983-2006 + Yield from Trial C1 from 1997-2009	2358	1953	2670
C3	C1 + YCS 1983-2006 + Legal catch from 1997-2009	2270	1890	2565
C4	C3 + IUU catch from 1997-2009	2245	1870	2535
b) Scenario		Trawl selectivity 1997-2006 F (yr^{-1})	Trawl selectivity 2006-2009 F (yr^{-1})	Longline selectivity 2003-2009 F (yr^{-1})
F1	C1 parameters	0.0872	0.1154	0.0859
	Mean catch across trials in final year	2446	1997	2806
	Standard deviation of catch across trials in final year	424	384	490

Effects of illegal fishing

Since the beginning of the fishery, illegal fishing has been estimated to have taken 40% of the total removals of Patagonian toothfish from HIMI up to 2009. Some of the downward adjustments made to the catch limits on the legal fishery were a result of accounting for the impacts of the illegal activities. However, such adjustments were usually small as the cost of illegal fishing was spread over 35 years The results in table III do not reveal the impacts of illegal fishing in the future as those projections assume no further illegal operations .

In order to explore the potential future impacts on the legal fishery of illegal fishing if it were to occur, further projections were undertaken based on Trial C3 in table III. These projections added an illegal catch to the long-term annual yield (LTAY) resulting from the CCAMLR decision rule for that trial. The revised projections were used to determine, given an annual illegal catch, (i) the year when the depletion part of the decision rule would be activated and the legal fishery catch limit would be set to zero, and (ii) the catch performance of the legal fishery over the projection period where performance is judged as the aggregate legal catch up to the time of closure (years × LTAY) divided by the total aggregate legal catch in the absence of illegal fishing (35 years × LTAY). Figure 12 shows how sustained illegal activities at even only 1000 t on average per year could cause a greater than 50% reduction in the aggregate return to the legal fishery over 35 years and result in depletion of the stock and closure of the fishery after 16 or less years

The results on possible future effects of illegal fishing give insights into how much time is available, if overharvesting is occurring, to reduce catches before a fishery will need to be closed. The precautionary approach taken at HIMI has so far accommodated substantial uncertainties and, at times, significant inadvertent pressures on the stock in the early years. These pressures have now been rectified, including eliminating illegal fishing, with the long-term annual yield only 5% less than would have occurred if better knowledge was available at the outset.

Constant catch or constant F?

Consideration is given from time to time as to whether the fishery should be managed under a strategy of constant fishing mortality (constant-F strategy) rather than a constant-catch strategy. Table III shows results of such a strategy (Trial F1, which is based on Trial C1 but for constant F rather than constant catch). This indicates that the mean annual catch in a constant-F strategy when the stock is at equilibrium is approximately the same as that catch that would be delivered in a constant-catch strategy, indicating that there is little to be gained by adopting a constant-F strategy in this fishery. Notably, the constant-F strategy would result in inter-annual variability in the catch of 20% or more as the stock fluctuates. Moreover, uncertainty would increase because of the methods needed to determine the annual catch limit by applying F to uncertain estimates of 'current' stock structure and biomass.

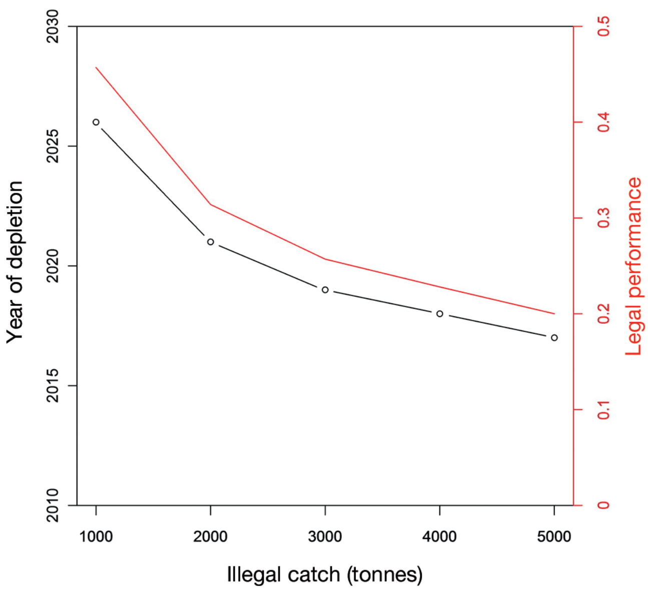

Figure 12. - The impact of illegal catches on future potential catch of the legal fishery for Patagonian toothfish at Heard Island and McDonald Islands. Projections based on Scenario C3 in Table III were undertaken by adding the illegal catch to the long-term annual yield (LTAY) resulting from the CCAMLR decision rule for Scenario C3. 2010 is the first year of the future projection period over which the LTAY is determined. 10 001 replicate projections were used for this assessment. The revised projections were used to determine (i) the year when the depletion part of the decision rule would be activated and the legal fishery catch limit would be set to zero (black line, left axis), and (ii) the catch performance of the legal fishery over the projection period (red line, right axis) where performance is judged as the aggregate legal catch up to the time of closure (years × LTAY) divided by the total aggregate legal catch in the absence of illegal fishing (35 years × LTAY). Points indicate the illegal catches added to the long-term annual yield.

Managing bycatch

An important component of ecosystem-based management is to minimise effects on non-target taxa. At HIMI, requirements vary between taxa depending on their status under legislation but the overall strategy to manage bycatch is the same as the principles in CCAMLR (SC-CAMLR, 2001a, paragraph 5.109) . The primary aim for managing bycatch is to have a negligible impact on those populations wherever possible. This has been translated into the following: i) identify and, where possible, implement strategies to avoid bycatch, either as season/area closures or as move-on provisions where bycatch rates are high; ii) if avoidance is not possible, then develop methods to mitigate bycatch; and iii) when needed, set catch limits that will suitably take account of uncertainty and achieve the conservation requirements for bycatch species.

Seabirds and marine mammals in the region are protected species under Australian legislation. Albatross and petrels are given special consideration because of the threatened or endangered status of many species. This led to the development of a Threat Abatement Plan under the EPBC Act aiming to substantially reduce, if not eliminate the threats to the species in order to provide them with as much opportunity to recover to unthreatened levels. Avoidance of incidental mortality of seabirds and marine mammals in fisheries is the primary goal of the TAP for albatross and petrels at HIMI (AAD, 2006). The primary avoidance strategy currently employed is to close the area to longline fishing during the breeding season in summer (October through March). Other measures to minimise the levels of interaction include (DEWR, 2007): no offal discharge requirement which limits provisioning opportunities for wildlife; limit (up to three) on the number of boats allowed to operate in the HIMI fishery at any one time; longline operations include using integrated weighted lines for rapid sinking of lines, paired streamer lines, blue snoods, and brickle curtains to discourage birds from approaching lines; for midwater trawl operations, no midwater trawling occurs in February or March and can only occur at night in the other months; lighting is minimised on all vessels to reduce the risk of seabirds colliding with them; and plastic packaging bands are prohibited.

Measures to minimise interactions have been present since the beginning of the fishery and the majority of these measures were first instigated by Australian legislation in the HIMI, before being incorporated by CCAMLR to broader requirements for all CCAMLR members. Incidental mortality of marine mammals and birds arise from time to time in the HIMI but remain negligible with less than 16 seabirds and 13 marine mammals dying in the fishery since the beginning.

For finfish and elasmobranchs, bycatch is avoided where possible but a level of incidental catch is permissible. Assessment of bycatch limits were undertaken using the Generalised Yield Model and based on the assessments of abundance from the original trawl surveys in 1990-1993 and life history parameters largely taken from the literature (Constable *et al*., 1998). Currently, the main bycatch species and their catch limits are *Channichthys rhinoceratus* Richardson 1844 (150 t), *Lepidonotothen squamifrons* (Günther 1880) (80 t), *Macrourus* spp. (320 t for all species combined) and *Bathyraja* spp. (120 t). For any other taxa, there is a catch limit of 50 t. Due to their approximate nature, these limits have not been regarded as being sustainable if they were to be taken at that level each year. To help avoid a bycatch species catch limit forcing a closure of the fishery and to avoid localised depletion of bycatch species, measures are used to trigger a move out of an area if bycatch rates are too high. If in the course of directed fishing the bycatch of *C. rhinoceratus*, *L. squamifrons*, *Macrourus* spp., *Bathyraja* spp. or *Somniosus* spp. exceeds 2 t, or of any species exceeds 1 t, the vessel is required to move at least 5 nautical miles away for at least five days. Elasmobranchs that are assessed to have a good chance of survival after being caught are also tagged and

released. As a consequence, bycatch levels are generally low (< 10% by weight of the toothfish catch) and less than 50% of the bycatch limits for any single taxon.

A final component of managing bycatch has been to assess the risk of the fishery impacting on species that only rarely are caught (Constable *et al.*, 2003; AFMA, 2009). Comprehensive risk assessments have been undertaken for all bycatch taxa recorded in the fishery or form the region using the methods described in Hobday *et al.* (2011), and indicated that no additional taxa require special attention in terms of assessments or mitigation strategies.

Spatial management to conserve biodiversity and habitats

Ecosystem-based fisheries management usually relates to managing the impacts of the removal of production, either as target, bycatch or by-product species (FAO, 2003). On a broader level, integrated ecosystem management is managing the potential conflicts between sectors, of which fisheries is one, and ensuring that multi-sectoral, multiple use management does not cause compound (synergistic) impacts on the ecosystems. While this is increasingly the goal, there is also recognition that fisheries and other sectors can have long-lasting unpredictable impacts on ecosystems not limited to temporary shifts in production and effects on food webs. There is an expectation that ecologically sustainable development results in ecosystems being able to mostly recover once activities cease. However, unforeseen interactions may potentially result in marine activities altering the future amenity or unforeseen utility of marine ecosystems in which those activities occur and changing the capacity of those ecosystems to be resilient to and/or adapt to (for example) climate change impacts.

The requirements for 'safeguarding the future' are generally articulated as conservation aims through some sort of area protection. However, the goal is not intended to be just the maintenance of species as they are at present. Future amenity and utility of marine ecosystems lie in ensuring the maintenance of ecosystem structure and function combined with retaining the potential for species to adapt to and evolve with new environmental states arising from global change. This will be more complex than retaining a few areas where most species are found but will need to include ranges of habitats and environmental conditions that will encompass the varied nature of the marine environment. A range of environmental conditions is needed because of our inability to predict which sets of those conditions will be present in the future. Similarly, the places where most species are found together may not be the optimal places for some of those species (Constable *et al.*, 2010). Thus, maintaining a range of conditions will hedge against uncertainty in both the requirements of taxa as well as the conditions in the future.

Also, safeguarding the future does not need to be seen as an impost on existing sectors of use when protected areas, if large enough, can be used to provide a benchmark for marine ecosystem status and change. Management of other sectors can be undertaken with reference to this in order to secure their long term sustainability.

Australia determined to establish a National Representative System of Marine Protected Areas (NRSMPA) in Commonwealth waters in 1991 as part of its 'Ocean Rescue 2000' initiative (DASET, 1992) and the Intergovernmental Agreement on the Environment[4]. The foundation principles of this system were for it to be comprehensive, adequate and representative (CAR: see Constable *et al.*, 2010 for discussion) (CoA, 1996; ANZECC TFMPA, 1999). In light of this, work was undertaken to designate a marine reserve to be part of the NRSMPA in the vicinity of Heard Island and McDonald Islands (Meyer *et al.*, 2000), which was established in 2002 (see Welsford *et al.*, 2011b for a complete description).

The HIMI Marine Reserve (Fig. 1) was the third Commonwealth marine reserve adopted as part of the NRSMPA and, at the time, the largest International Union for the Conservation of Nature (IUCN) Category 1a marine reserve in the world. It was designed to meet the CAR criteria, particularly with a view to having areas fully representative of ecosystem structure and function, but also to provide reference areas for monitoring the effects of global change on the marine environment. It also was configured in such a way as to be able to better understand the effects of fishing (or other activities) on the region – most biophysical areas could be monitored inside and outside the marine reserve.

In addition to the marine reserve, a Conservation Zone was established (4 smaller areas – Fig. 1), which included areas for which further clarification was needed as to whether conservation values within the zone warranted inclusion in the marine reserve or whether fishery resources in the zone should remain accessible. This process has almost been concluded following further work in the conservation zone that compared the habitats with those nearby in the reserve and those outside. This process has been a useful one because it has not prejudiced future options – activities were closely managed to ensure that conservation and fishery values have been retained throughout the process. Nevertheless, enough fishing activity and research was allowed in the conservation zone to assess fishery potential while not impacting on the habitats (Welsford *et al.*, 2011b).

As part of the management and conservation of habitats at HIMI, the need for further measures to understand and, if needed, mitigate interactions of fishing gears in areas outside the marine reserve may be important. One of the primary challenges to assessment of the impact of demersal fishing to Southern Ocean benthic ecosystems has been the

[4] Full text of the agreement is available at: www.environment.gov.au/about/esd/publications/igae/index.html.

lack of empirical data on the nature and extent of interactions between fishing gears and the benthos, and a lack of data on the distribution of habitat types – both where fishing occurs and within the reserves.

A collaborative project was established in 2006 to assess the vulnerability of and risks to habitats in the Southern Ocean to impacts by different demersal fishing gears – trawl, longline and traps. This study has produced the necessary technology for easy use by observers on commercial fishing vessels to observe the nature of demersal fishing interactions (trawls, longlines and traps) with benthic habitats and species during commercial fishing operations (Kilpatrick *et al*., 2011). With this gear combined with research sampling using beam trawls, the project is undertaking the following (Ewing *et al*., 2010): seascape assessment, which is the identification of the relevant attributes of the seascape such as the benthic assemblage within and outside the marine reserves, and the extent to which demersal fishing activity overlaps those attributes; vulnerability assessment, an evidence-based assessment of the nature and extent of interactions between the demersal fishing gears used and the benthic species and assemblages within the seascape; impact assessment, which is the prediction of the possible consequences to the dynamics of the benthic assemblages resulting from the extent of demersal fishing activity; and management strategy evaluation, which is the evaluation of the performance of management and data collection strategies designed to avoid significant adverse impacts to benthic ecosystems and/or unacceptable consequences to the attributes of the seascape.

Conserving benthic habitats became a topical issue in CCAMLR and the United Nations General Assembly (UNGA) in 2006. In particular, UNGA resolved that bottom fisheries on the high seas should avoid having significant adverse impacts on vulnerable marine ecosystems (VMEs) (UNGA, 2006). Since then, CCAMLR has grappled with the issue of VMEs, implementing measures for the areas beyond national jurisdiction (Constable and Holt, 2007; SC-CAMLR, 2007, 2008, 2009). This discussion is important generally because it helps to articulate the uncertainties surrounding the conservation of benthic habitats and that the attributes of benthos are not solely related to food web dynamics and productivity. It is also important to consider all forms of fishing and whether or not mitigation is needed given the habitats in which fishing may occur, not just to focus on trawling in an omnibus fashion, which has been a tendency in the debate so far.

Despite the paucity of data on the specific ecologies of most benthic species in the Southern Ocean, a practical approach can be developed to evaluate fishing strategies aimed at achieving the objective of avoiding significant adverse impact on benthic assemblages (VMEs)(Constable and Holt, 2007; Constable, 2009; Constable, 2010). This objective can be translated into a simple operational objective consistent with the objectives of CCAMLR (Article II) to maintain the quality of habitats above the level that can naturally restore the original structure and function within 20-30 years. It does not require habitats to be categorised as "vulnerable marine ecosystems" or "invulnerable marine ecosystems", a categorisation fraught with difficulty (Constable and Holt, 2007). Instead, it means that habitats for which this would not easily be met would be more vulnerable than those for which the objective might be met most often. Such an approach allows for appropriate scaling of responses to the UNGA resolution without having to determine whether an area is included or excluded from consideration.

A simulation approach has been developed for assessing whether harvest strategies will meet the operational objective (Constable, 2009; Constable, 2010) consistent with the approach adopted for target species described above. In place of a population model, a spatially-structured habitat model is used. The model allows integration across uncertainties associated with spatial distribution of habitats, habitat dynamics, including usual intra- and inter-specific interactions of sessile organisms, the potential interaction of fishing gears with those habitats and species and the potential dynamics of recovery, including the need to consider the time lags of recovery that may be associated with ecological succession towards the assemblage structure present prior to fishing, as well as the potential need to retain connectivity between patches. Multiple habitat types with different dynamics can be explored simultaneously. Clearly, choices need to be made for these models as to the spatial resolution of habitat attributes and extent, the behaviour of the fishery and its interactions with the habitats and management units. Nevertheless, assessments can be made as to the likelihood of the habitats being able to recover should fishing cease and whether the dynamics of habitats within a region would be appreciably impacted by further demersal fishing activities. This model can be used to assess different management strategies, including the use of within-season move on rules and post-season assessments, such as those in use by CCAMLR (SC-CAMLR, 2010a), and the data requirements to make those strategies successful in meeting the objective.

The discussion above provides a context in which the mitigation of impacts on sensitive benthic habitats are being considered for HIMI. Decision rules for actions in the HIMI fishery given within-season observations and/or post-season assessments of impacts are in the process of being developed within the project but will need to incorporate the risk of failing to meet the objective, as in the decision rules for toothfish and icefish above. For HIMI, the important question is whether additional measures (whether by avoidance or mitigation) are needed to conserve benthic habitats given

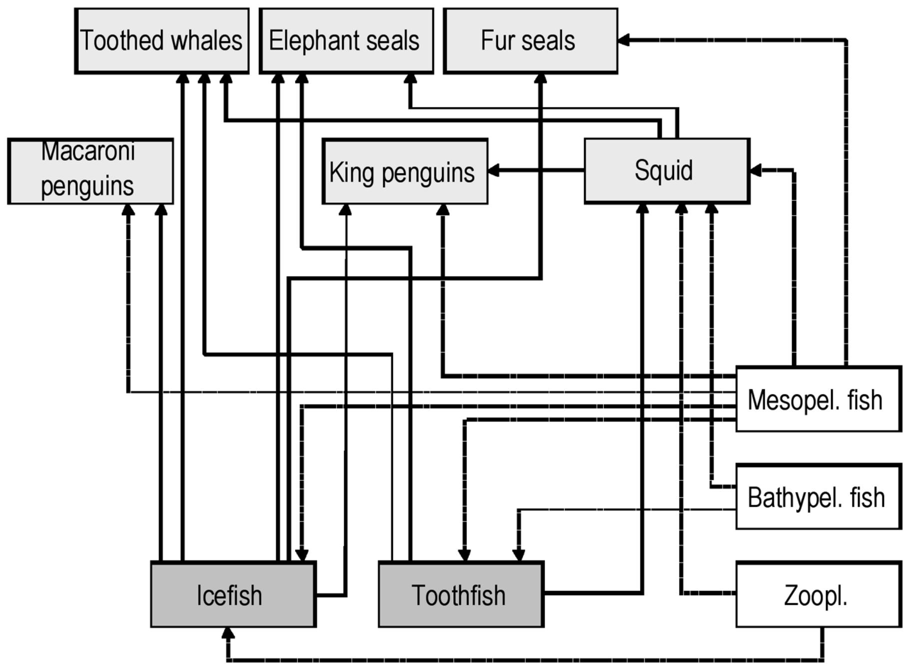

Figure 13. - Stylized foodweb, not including protists, for the marine ecosystem in the vicinity of Heard Island and McDonald Islands. Only the dominant pathways are shown to identify the major linkages in the food web. Mesopel. = mesopelagic, Bathypel. = bathypelagic, Zoopl. = Zooplankton.

the protection that may already be available to those habitats in the marine reserve.

Indirect effects on food webs

A challenge for ecosystem-based fisheries management is to understand the indirect effects of removing target and bycatch species on food webs or of fishing impacts on habitats (FAO, 1996). While this is a requirement of CCAMLR and Australian legislation, it is not easy to implement. In 1997, a workshop was held at the AAD to examine how to address this issue for Australia's subantarctic fisheries at Macquarie Island and HIMI (de la Mare, unpubl. report). Three approaches were identified: i) examine the potential escapement of Patagonian toothfish from fisheries to see if it is likely to be sufficiently high to sustain predators, ii) undertake field research programs to better understand the linkages between target species and the broader food web, and iii) develop food web models to explore the potential indirect impacts of fisheries on the food web and to evaluate different management strategies in light of the considerable gaps in knowledge.

In the early stages of the fishery at HIMI, the primary target was juvenile Patagonian toothfish. At the time, stomach analyses of elephant seals suggested juvenile toothfish may be important prey for young elephant seals foraging near to HIMI (Green and Burton, 1993; Slip, 1995). In CCAMLR, the reference point for target species considered to be important prey in the food web had been arbitrarily set at 0.75 until work was undertaken to ascertain a suitable reference point for the target species (initially determined for krill, see Constable *et al*., 2000 for discussion). Using the assessment projections for Patagonian toothfish in 1997, it was found that median escapement of juveniles of the size taken by elephant seals was likely to be greater than 80%, which was higher than the CCAMLR target for prey (Constable *et al*., 1998). A reassessment has not been undertaken but the fishery is now catching older fish using longlines, which would suggest long term escapement of juveniles will now be greater than that again.

A number of field programs to examine marine foodwebs at HIMI have been undertaken between 1987 and 2004. The early programs are summarised in Green (2005). In 2003-2004, an integrated marine ecosystem study was undertaken to simultaneously monitor land-based predator movements and diet in conjunction with ship-based monitoring of the biota in the areas in which foraging occurred (Gales and Constable, 2004; Gales *et al*., 2006). At present, results have been published on oceanography (van Wijk *et al*., 2010), fish populations (Williams *et al*., 2011), tracking of marine mammals and birds (Frydman and Gales, 2007), and the foraging ecology of penguins (Wienecke and Robertson, 2006; Deagle *et al*., 2007; Deagle *et al*., 2008), flying birds (Lawton *et al*., 2008) and seals (Casper *et al*., 2007; Casper *et al*., 2010; Staniland *et al*., 2010).

The development of food web models to support management is in its infancy (FAO, 2003; Plaganyi, 2007) . However, there is sufficient understanding of the food web from the 2003-2004 study and other ecosystem studies on the Kerguelen plateau (e.g., Pruvost *et al*., 2005) to develop a food web model of the region to form the basis for evaluating ecosystem-based management strategies that achieve broader objectives for sustaining the ecosystem (Constable,

2001, 2004; Constable and Candy, 2008 and see below). The view of the food web at HIMI at present is summarised in figure 13, noting that depth stratification of taxa will be important to consider in determining the relative overlap of predator foraging areas with prey availability.

Management System

Since the inception of CCAMLR, human activities in the vicinity of Heard Island and McDonald Islands have included fishing, tourism and scientific research. With the development of a fully subscribed commercial fishery in the late 1990s and the substantial illegal fishing that occurred between 1996 and 2005, the complexity of the task of managing the marine environment, and the size of the active stakeholder constituency has increased dramatically (e.g., see an overview of the Australian Government approach to fisheries management in Wilson *et al*., 2010).

Continued investment in four features of the management system have contributed to the successful implementation of the precautionary approach: investment in sound and sufficient data collection programs, adoption of procedures for deciding on harvest strategies and habitat management requirements that take account of uncertainty, stakeholder participation in policy development, decision-making and research, and a commitment to compliance with and enforcement of regulations.

Data collection

The elaboration of strategies to achieve ecologically sustainable fisheries and the development of marine reserves was facilitated by the implementation of a targeted data collection program, which began prior to fishing and has been active throughout the course of the fishery. This has involved fishery independent surveys as well as acquisition of data through an observer program. By and large, it has been a partnership between fishing industry stakeholders and scientists at the AAD, with funding support at various times from Australian Fisheries Management Authority, the Australian Fisheries Research and Development Council and the Australian Commonwealth Department of Environment, and participation at times from the Australian Commonwealth Scientific and Industrial Research Organisation.

Importantly, the fishing industry stakeholders support this research and monitoring through providing annually 20 days of ship time, when commercial vessels undertake research according to the agreed annual research plan (see below), which includes the substantive annual random stratified trawl survey of stocks in the vicinity of Heard Island. Also, a fishery observer from the Australian Fisheries Management Authority (AFMA) observer program and a data collection officer are on each vessel participating in both the fishery and the research program to measure fish and bycatch, conduct the mark-recapture program of key species, monitor wildlife (marine mammal and bird) interactions and to undertake other tasks important for the management and research requirements in the fishery. Additionally, during the research cruises, industry have regularly either provided extra crew support for the two observers, or carried a third government observer for that trip, to ensure the workloads are achievable. The research plan and the observer program have been operating at this level since the beginning of the fishery and have provided the data essential to the ongoing refinement of the stock assessments and for determining suitable strategies for mitigating impacts of fishing on seabirds, marine mammals and benthic habitats.

Procedures for determining harvest strategies

A great challenge for managers of the region is to understand whether the various strategies will achieve their sustainability and conservation objectives in the long term. The implementation of assessment and catch setting methods that take account of uncertainty (above) provided the means for developing the fishery despite little knowledge at the outset. At present, the fisheries for Patagonian toothfish and mackerel icefish are considered to be compliant with the principles of sustainability and conservation (DEWR, 2007; Patterson *et al*., 2010). However, uncertainties still remain on the key drivers of the stocks and the predator-prey dynamics of the region, not least of which are the linkages with other stocks on the Kerguelen Plateau. As the physical conditions of the region are already changing, with the dramatic southward movements of ocean fronts (Sokolov and Rintoul, 2009), a better understanding is needed of the efficacy of these strategies given the larger uncertainties on stock structure and climate change impacts on the dynamics of key taxa and the food web.

A feedback management system is needed to provide the mechanisms for changing harvest strategies in response to new information or to signals of changes in stock dynamics or ecosystem structure and function that might arise from fishing or other pressures and/or climate change impacts. Such a system requires monitoring of key indicators in the field to signal when and what changes to the harvest strategies are required. A Southern Ocean Sentinel program has been discussed as providing an integrated and efficient field monitoring program to detect such signals, particularly climate change impacts (Fig. 14, Constable and Doust, 2009) and is part of an international program on Integrating Climate and Ecosystem Dynamics in the Southern Ocean (ICED) for its further development[5]. The Kerguelen Plateau features as an important location where monitoring will need to be undertaken. Consideration is now being given to what might

[5] Documentation including the 2009 workshop report is available at www.antarctica.gov.au/science/southern-ocean-ecosystems/southern-ocean-sentinel-workshop.

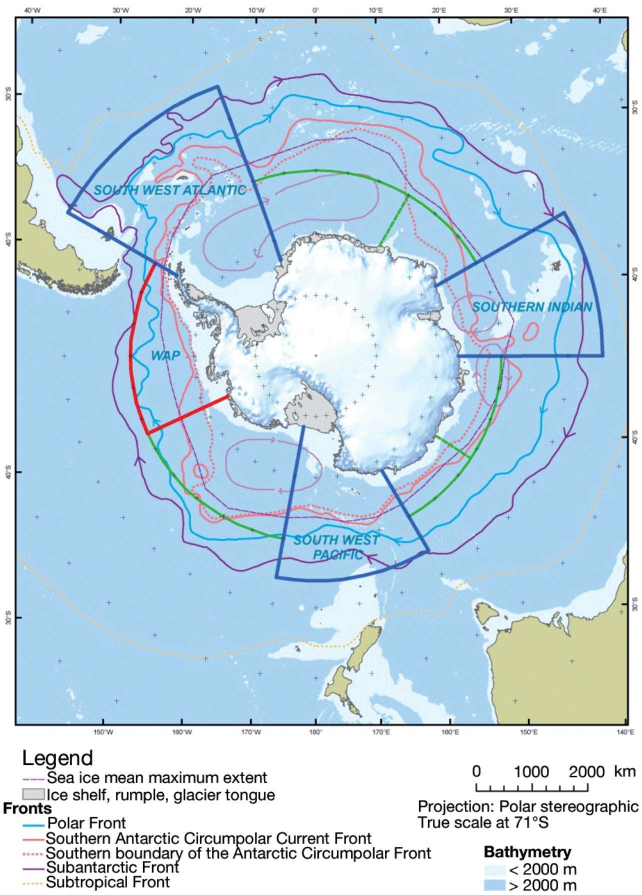

Figure 14. - Possible spatial configuration of a Southern Ocean Sentinel for measuring climate change impacts on Antarctic and Southern Ocean marine ecosystems (Constable and Doust, 2009). Four main areas are West Antarctic Peninsula, South-West Atlantic, Southern Indian and South West Pacific. Those areas outlined in green indicate coastal areas that could be used to help differentiate between hypotheses of change in the high latitude areas. The Kerguelen Plateau features as an important area where change is already occurring.

be efficiently monitored in the region as part of the Southern Ocean Sentinel and for use in feedback management, including using the reference areas in the HIMI Marine Reserve.

Coordinated research between Australia and France is facilitating a better understanding of the dynamics of stocks and the ecosystem on the Kerguelen Plateau. It will be integral to the success of developing long-term feedback management procedures for Patagonian toothfish and mackerel icefish fisheries in the region.

Overall, this work forms part of an overall research program to evaluate alternative management strategies to identify the best strategy for meeting ecologically sustainable criteria in the long term and for being capable of responding to climate change impacts on the region. Such evaluations are an important component of the precautionary approach as they identify the potential weaknesses in a prospective management system for its ability to achieve sustainability and conservation objectives. As a result, the weaknesses can be rectified before they become a problem in reality. Evaluation of these strategies is being done using computer simulations and the methods now known as Management Strategy Evaluation (MSE: see de la Mare, 1998; Cooke, 1999; Smith *et al*., 2007 for details of these methods and He and Furlani, 2001 for their application in the Macquarie Island toothfish fishery).

Stakeholder participation

An important element of the management system has been active stakeholder input to the development of research priorities, management strategies and policies. Stakeholder forums include those related to CCAMLR (CCAMLR Consultative Forum), fisheries (Subantarctic Resource Assessment Group and the Southern Ocean Management Advisory Committee providing advice to the Australian Fisheries Management Authority) and conservation (HIMI Stakeholder Group advising on the HIMI Marine Reserve and Conservation Zone; Albatross and Petrel Threat Abatement Team). The consultative and co-management processes provide the mechanisms for debating the relative importance and possible impacts of proposed policies and regulations on stakeholders and also allow joint formulation of priorities for research to help resolve issues, such as clarifying the conservation and fisheries values of the HIMI Conservation Zone). As a result of these processes, the need for compliance with management measures is jointly understood, agreed and achieved.

Enforcement

Since the late 1990s, Australia, with France, has been committed to eliminating illegal fishing activities from the Kerguelen Plateau. This sustained commitment to enforce Australian regulations in its distant water territories is integral to the successful management of the region, resulting in clear benefits to the long-term value of the fishery and ecological sustainability (above).

CONCLUSIONS

The precautionary approach is often seen as an impost on fisheries. However, this review shows how the precautionary approach has resulted in the long-term sustainability of the fishery being secured at levels close to that which would have occurred if the current knowledge was available at the beginning of the fishery. A key lesson from HIMI is that ecological sustainability and long-term conservation can be achieved by having a responsive management system without having to know everything about the stocks and ecosystem before action can be taken; the fishery developed at a

pace that was commensurate with the level of understanding available at the time.

The experience at HIMI suggests that integration of management, science and stakeholders provides for the vigilance necessary to address issues before they become a problem. This relationship is essential for good environmental and industrial sustainability outcomes, thereby avoiding a common theme at present in fisheries which is to need radical downward adjustments to fisheries, including closures, in order to restore stocks to ecologically sustainable levels.

Overharvesting through illegal or other activities can cause substantial reductions in the long-term value of the fishery if it occurs at even marginal levels. Importantly, once the stock nears being depleted, continued overharvesting can lead to precipitous declines in catches in only a few years. Continued management measures, including enforcement, are needed to avoid this scenario.

While many uncertainties that plague fisheries have been resolved in the approach at HIMI, two important challenges are being addressed at present for fisheries in the vicinity of HIMI: (1) what harvest strategies will achieve the ecologically sustainable objectives given the possible stock structures of Patagonian toothfish and mackerel icefish on the Kerguelen Plateau; and (2) what impacts will climate change have on stock and food web dynamics in the region and how will these affect fishery and conservation strategies and objectives? Finally, a key question in developing strategies to deal with these challenges will be how to collect data in an integrated way across the Kerguelen Plateau that can provide clear and unambiguous signals of change in status of the stocks and the ecosystem and the respective roles of fisheries and climate change in causing those changes.

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